

**KNOWLEDGE REUSE FOR INNOVATION –
THE MISSING FOCUS IN KNOWLEDGE MANAGEMENT:
RESULTS OF A CASE ANALYSIS AT THE JET PROPULSION LABORATORY**

Abstract -- Research on knowledge management focuses on the capture, transfer, and reuse of knowledge. In this paper, we make a distinction between reuse of knowledge for routine tasks (e.g., use of templates, boilerplates, and existing solutions) versus reuse that stimulates knowledge synthesis and innovation (e.g., searching a database to find new ideas to combine with existing knowledge). We argue that very little research has focused on the latter type of reuse and as a result leave questionable the extent to which we know how to facilitate reuse for innovation. We describe the results of six case analyses of reuse for innovation at JPL. From this research, we have derived a model that identifies 9 factors likely to encourage knowledge reuse. In addition, our research yields a process model that helps to explain how the reuse process unfolds in an innovation context. Implications of these two models for research and practice are presented.

I. INTRODUCTION

How organizations create, retain, transfer and reuse knowledge has been a subject of increasing interest to organizations in recent years (Argote, 1999; Argote, Ingram, Levine, & Moreland, 2000; Huber, 1991). Strategic considerations that tie the transfer of knowledge to strategic necessity have fueled the fire. Under the environment of globalized capitalism, firms require the effective transfer and use of knowledge in order to function effectively (Drucker, 1991, Ch. 1; Giddens, 1991, Ch. 1; Reich, 1991, Ch. 7-10). It has been theorized that firms that effectively transfer knowledge, while preventing competitors from tapping into their knowledge resources, are more successful than those that do not effectively manage their knowledge resources (Lippman & Rumelt, 1982; Winter, 1995; Zander & Kogut, 1995).

This recognition of the importance of knowledge transfer to a firm has led to the development of knowledge management systems intended to enhance the knowledge transfer process. Knowledge management systems are defined as

“information systems designed specifically to facilitate codification, collection, integration, and dissemination of organizational knowledge.” (Alavi & Leidner, 1999).

A typical knowledge management system involves a data (or knowledge) base, a cataloguing system, version control, document access control, a user-friendly search and navigation capability, and a possible variety of advanced features such as email notification or commenting. Because knowledge management systems involve the cataloguing of knowledge for later reuse, most knowledge management systems today have been developed to enhance the efficiency of a work process. As such, documents are captured and catalogued to support likely known future reuses, such as consultant services or administrative templates (Davenport, Jarvenpaa, & Beers, 1996). Ernie is an example of such a knowledge management system in which consultants use

keyword and advanced Boolean searches to identify solutions used previously for clients with similar problems.

Knowledge transfer is used not only to support process efficiency; but innovation as well (Darr & Kurtzberg, 2000; Pennings & Harianto, 1992) both within and across firms (Garud & Nayyar, 1994; Gilbert & Cordey-Hayes, 1996; Szulanski, 1996). Knowledge transfer for innovation involves more than simply representing knowledge in a repository for likely known future uses and having reusers simply search the repository. Innovation, by definition, means the use of knowledge in unknown future contexts and thus simple searches of any repository are unlikely to yield innovative outcomes. Instead, what is required is the questioning of implicit assumptions, constraints, and principles of the knowledge as it was used in one context to determine the extent to which the knowledge can be applied (or recontextualized) to an alternative context *Ann insert reference* (REF?). This process of recontextualizing the knowledge is likely to leave the initial knowledge fundamentally altered in order to incorporate the new contexts. Typically, this process of questioning - and then altering - the original knowledge is performed exclusively by humans (sometimes with the aid of a coordination tool) in hallway discussion, phone meetings, or formal brainstorming sessions. The concept of using a knowledge management system that might contain a repository of knowledge that will change as it interacts with reusers as well as help reusers create innovative connections among disparate concepts is still advanced thinking. (Davenport et al., 1996).

Before such a knowledge management system for innovation can be developed, however, we must have a much clearer understanding of how knowledge is transferred within an innovation context so that suggestions for knowledge management systems and their use can be better targeted. Does knowledge transfer in innovation proceed in similar ways as knowledge

transfer for known or routine purposes? Are the critical factors influencing the process the same? These are the questions this paper is intended to address. First we review the literature on existing theories of knowledge transfer to determine which aspects of the models might apply to transfer in an innovation context. Then, we present the results of an initial six-case analysis of knowledge transfer in innovation to develop a set of factors that appear to affect knowledge transfer in innovation.

II. RATIONALE & LITERATURE REVIEW

What is knowledge?

Knowledge has been defined in a variety of ways. Based upon the work of Nonaka (1994), Huber (1991) and Alavi (1999) adopted the following definition (Huber, 1991; Nonaka, 1994): “Knowledge is justified personal belief that increases an individual’s capacity to take effective action.” (Alavi et al., 1999: 4) This definition is consistent with Churchman’s (1972) definition of knowledge and his concept that knowledge does not reside in a collection of information, but resides in the mind of the user (Churchman, 1972). A more expansive, and functionally more useful definition was developed by Davenport and Prusak (1998), “Knowledge is a fluid mix of framed experiences, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. ... It often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms.” (Davenport & Prusak, 1998: 5)

There has been a multitude of research on knowledge management. We have classified this research in to 6 streams:

1. Knowledge creation and knowledge management models
2. Common ground
3. Organizational learning
4. Resource based view: knowledge capital as an organizational asset

5. Knowledge transfer through alignment of networks
6. Innovation and developmental process

Knowledge Creation and Knowledge Management Models

Knowledge creation models have been concerned with how tacit and explicit knowledge from individuals, groups, and entire organizational entity are combined to generate process, product and technological innovation (Kogut & Zander, 1992). Underlying this model has been the debate concerning the sharp or blurred distinction between tacit and explicit components of knowledge. Nonaka and Takeuchi (1995) and Spender (1996) separate the tacit and explicit components of knowledge. Spender (1996) suggested a 'pluralistic epistemology' that captures a further segmentation of the different types of knowledge into explicitly articulated knowledge and implicitly manifested knowledge. Four types of knowledge are noted:

- 1) conscious (explicit knowledge held by the individual)
- 2) objectified (explicit knowledge held by the organization)
- 3) automatic (preconscious individual knowledge)
- 4) collective (highly context-dependent knowledge which is manifested in the practice of an organization).

Using these distinctions, a view of knowledge transfer has been promoted that involves transforming tacit to explicit knowledge. (Hedlund, 1994; Kogut et al., 1992; Sherman & Lacey, 1999). For example, Nonaka & Takeuchi (1995) propose a four-stage knowledge creation (i.e., transfer) model:

- 1) Socialization, experiencing tacit knowledge through apprenticeship or training.
- 2) Externalization or articulation; linking tacit knowledge with explicit knowledge and articulating knowledge to other team members;
- 3) Combination of different explicit ideas in a process of standardization such as a manual or knowledge management base; and
- 4) Internalization; extracting tacit knowledge from the newly created knowledge base, putting new knowledge to use, developing new routines and internalizing the changes.

Formalized communication structures and teambuilding interventions that improve the ability of team members to transfer, capture, and make tacit knowledge explicit may be a source of sustained competitive advantage (Bresman, Birkinshaw, & Nobel, 1999; Sherman et al., 1999). A systems perspective of knowledge creation that enhances competitive advantage has been modeled by Von Krogh, Ichijo and Nonaka (2000) in their Knowledge Enabling and Creation: 5 x 5 grid. The five enablers, (1) Instill a Vision, (2) Manage Conversations, (3) Mobilize Knowledge Activists, (4) Create the Right Context, and (5) Globalize Local Knowledge, meet the five creation steps, (1) Sharing tacit knowledge, (2) Creating Concepts, (3) Justifying Concepts, (4) Building a Prototype, and (5) Cross-leveling knowledge (Von Krogh, Ichijo, & Nonaka, 2000).

In contrast to the model of knowledge transfer in which tacit knowledge must be made explicit, Polanyi (1966) favors a blurred distinction between tacit and explicit knowledge, noting that there is a tacit component to all knowledge (Kogut et al., 1992; Teece, 1981). Tacit knowledge is often held sub-consciously until it is used (Reed & deFillippi, 1990). Tsoukas asserts that articulated knowledge is based upon an unarticulated background including social practices that are internalized and cognitive in nature (1996). In an organization, the culture, routines, stories and the "invisible assets" of the organization are common repositories for tacit knowledge (Harris, 1994; Itami, 1987; Nelson & Winter, 1982; Ouchi, 1980). Thus, the knowledge transfer process is one of sharing stories and interpretations rather than making knowledge codified and explicit (Brown & Duguid, 1998).

From this perspective, the knowledge transfer process may occur through the ability of an organization to combine both tacit and explicit knowledge. In this concept, knowledge is recombined from both inward and outward sources (Kogut et al., 1992). Kogut and Zander note a

circular connection between exploitation (use of internal knowledge) and exploration (invention, outward search).

“...an important limitation to the capability of developing new skills is the opportunity (or potential) in the organizing principles and technologies for further exploitation. Eventually there are decreasing returns to a given technology or method of organizing and there, consequently, results an incentive to build new, but related skills.” (Kogut et al., 1992: 385)

We adopt the Polanyi position that tacit and explicit knowledge should not be differentiated in the knowledge transfer process (Polanyi, 1966), especially as it pertains to the innovation context. This suggests that a knowledge transfer process for innovation needs to consider both the tacit and explicit elements of the knowledge simultaneously.

Common ground

Clark's (Clark, 1996; Clark & Brennan, 1993) theory of language use suggests that veridicality of communication is more likely when both parties to the communication have a "common ground". Common ground can be defined as the beliefs, knowledge and suppositions that the parties believe they share about the joint activity. In this theory, common ground is developed through interactions and communication that include requests, promises, assertions, questions, apologies, declarations, and responses.

The greater the common ground between the knowledge reuser and the knowledge generator, the more likely that reuse will occur (Majchrzak, Rice, Malhotra, King, & Ba, 2000). Common ground can be facilitated in a variety of different ways. While some authors suggest that common ground is primarily created through in-person interactions McGrath (REF?); Clark (REF?), others (e.g., Olson, (REF?)) have identified ways in which common ground can be created electronically, through the use of shared artifacts such as common stories or myths, shared documents, or shared metaphors (Brown et al., 1998). While Olson (REF?), Brown &

Duguid (1998) and Hutchins (REF?) limited their discourse on shared artifacts to those shared among communities of practice, it is possible to conceive of a situation in which shared artifacts could be used to transfer knowledge across different communities of practice, such as when a meteorologist uses a basic physics principle as the shared artifact to understand and evaluate the contribution of structural engineer.

In the innovation context, common ground can be defined by the mutual understanding of the project objective, technical constraints, organizational constraints, analytic process for problem solving, mutually understood goals, and similarity of dedication to resolution. In addition, common ground can also be conceptualized as the set of shared norms and behaviors, defined as people behaving in ways expected by others (Ouchi, 1980; Tsoukas, 1996). In the knowledge transfer and reuse context (Davenport et al., 1998; Majchrzak et al., 2000) such norms might include who has access to what knowledge, how is the quality of the knowledge evaluated, and what attributes of the knowledge should be captured for later use.

This set of theories then suggest that, for a knowledge transfer process focused on generating innovation, the process of knowledge transfer should convey, and encourage the development of, a common ground between knowledge generators and potential knowledge re-users. In an single community of practice, such common ground might be assumed; however, when the innovation crosses communities (as it should for revolutionary innovation to occur), the knowledge transfer process (and the enabling knowledge management system) should either facilitate the development of a common ground or allow re-users to translate their own common grounds across these communities.

Organizational learning

According to Weick (1995), organizational learning involves an openness to the notion that different people may have different views on the reality of the same fact. This openness may create a great deal of ambiguity, but it is necessary to accept ambiguity in order to achieve innovation. A variety of interpretations may lead to additional learning opportunities (Huber, 1991). Senge elaborates on how to encourage this openness in the organizational learning process. He suggests five types of behaviors: systems thinking, clarifying personal visions, shifting mental models, building a shared vision, and engaging the team in joint and open dialogue (Senge, 1990). Interpretations of information are dependent upon the way individuals diverge and converge in relation to the mental models of the group (Ireland, Hitt, Bettis, & DePorrás, 1987; Walker, 1985). In addition, the way information is framed will affect its shared meanings (Tversky & Kahneman, 1985).

This organizational learning perspective on the knowledge transfer process thus suggests that knowledge transfer for innovation will benefit from an openness that encourages and allows multiple perspectives on problems. This might be manifested in a knowledge management system by having diverse knowledge available to re-users or encouraging searches for alternatives

Organizational learning researchers have also focused on factors that trigger organizational learning. One such trigger is a re-user's perceived gap between actual and potential performance (Dosi & Marengo, 1993; Iansiti & Clark, 1994; von Hippel & Tyre, 1993); larger gaps force more organizational learning to occur. Another trigger is the institutionalized assumptions or norms that knowledge transfer and reuse is done for the benefit of the organization and this benefit will also accrue to the knowledge generator and knowledge reuser. Thus, for the knowledge transfer process in innovation, an important driver will be the presence

of factors that stimulate knowledge reuse, such as organizational incentives or performance gaps. Research on new product development has identified what might be the triggers for knowledge reuse in the innovation domain. Tatikonda and Rosenthal (2000) studied 120 "high-tech" new product development projects. They hypothesized

"that 'technology novelty' and 'project complexity' are central contributors to task uncertainty in the product development project context." (Tatikonda & Rosenthal, 2000: 76)

Technology novelty is the degree of familiarity of the developing organization with the technology involved in this specific development project. Project complexity is defined as the

"nature, quantity, and magnitude of organizational subtasks and subtask interactions posed by the project" (Tatikonda et al., 2000: 78)

This suggests that the novelty and complexity of the project may be triggers to reuse knowledge, when the reuse will help to reduce the uncertainty.

Resource based view: knowledge capital as an organizational asset

The resource-based view is an economic theory of the knowledge transfer in the firm. According to the resource-based view, the firm's resources and capabilities can be a source of "excess income" or "rent" generation (Wernerfelt, 1984)(Barney, 1991; Dierickx & Cool, 1989; Lippman et al., 1982). In the resource-based view of the firm, during product development the capacity for a firm to take action resides in its capabilities (Iansiti et al., 1994). To generate excess profits, according to the resource-based view, the firm should have as many different organizational capabilities as possible: the more capabilities; the more likely that excess profits will accrue (Verona, 1999)(Grant, 1996).

Capabilities that generate excess rent have been described as either functional or integrative (Verona, 1999), with both required.. Functional capabilities allow a firm to increase its knowledge base while integrative capabilities act as

“an adhesive by absorbing critical knowledge from external sources and by blending the different technical competencies” (Verona, 1999: 134).

This “absorptive capacity of the firm” (i.e., the firm’s ability to integrate across functional capabilities) has been noted as a major contributor to excess rent generation (Cohen & Levinthal, 1990; Grant, 1996; Iansiti et al., 1994; Kogut et al., 1992; Teece, Pisano, & Shuen, 1997)..

This perspective on knowledge management suggests, then, that a knowledge transfer process needs to ensure that individual knowledge is developed simultaneously with knowledge to integrate across the knowledge bases. For example, this may suggest that a more successful knowledge transfer process will be one in which individuals are encouraged to create a diverse and robust personal knowledgebase while simultaneously being provided clear guidance for integrating across the knowledge bases.

Knowledge Transfer Through Alignment of Networks

Social networks theory is theory and a methodology that has been used increasingly in management related published journal articles since the late 1980’s (Arrow, McGrath, & Berdahl, 2000; Athanassiou, 1999). It is based upon the sociological principles of interconnectedness of individuals, organizations, sub-groups, and teams. These interconnections may be informational, hierarchical, work related or social. McGrath and Argote (2000) present a framework for the networks and subnetworks of knowledge (Argote & McGrath, 1993; McGrath & L., 2000). According to the McGrath & Argote framework, knowledge is embedded in three elements basic to the organization: members (people), tools (hardware & software), and tasks (organizational goals and purposes). These elements may be combined in various sub-networks through coordination between or among the elements.

The overall pattern of member-task-tool relations (which Arrow, McGrath, & Berdahl call the coordination network) is composed of six sub-networks: the set of member-member relations (the member or social network), the set of task-task

relations (the task network), the set of tool-tool relations (the tool network), the set of member-task relations (division of labor or labor network), the set of member-tool relations (the role network), and the set of task-tool relations (the job network).(McGrath et al., 2000: 17)

These sub-networks can increase in complexity such that a member-task-tool network is a specific routine for certain members performing particular tasks with specific tools (McGrath et al., 2000). The framework suggests that improvement in organizational performance can be achieved through internal compatibility of the networks or congruence of organizational components (Argote, 1982; Leavitt, 1986; Nadler & Tushman, 1980).

For knowledge transfer in innovation contexts, then, this stream of research suggests that the compatibility of knowledge networks should be examined, especially as knowledge is embedded in the people, tools, and tasks. When incompatibility is apparent (such as when an ambiguous task is using a tool that allows little process freedom), then knowledge transfer will suffer.

Innovation and Developmental Process

Several theories are concerned with the process of innovation through technology adaptation. DeSanctis and Poole (1994) use adaptive structuration theory to discuss the interactive influences of social processes and technology. The pre-existing conditions of the task (complexity, interdependence), organizational structure (hierarchy), the group's internal structure (hierarchy, internal decision making) and the technology's features and intent will affect the way in which a technology is "appropriated"; appropriations that are more closely aligned with pre-existing conditions will be more successful than those not aligned (DeSanctis & Poole, 1994). Leonard Barton (1988) presents a slightly different view, in which the technology, delivery system, and organizational structure are likely to be initially misaligned; but over time with cycles of adaptations, the misalignments will be gradually reduced. Orlikowski (Ann, REF)

suggests that these cycles of adaptations are highly restricted to windows of opportunities while Majchrzak et al have found that cycles of adaptations occur in direct response to negative effects that result from misalignments, provided that the pre-existing structures were sufficiently malleable for adaptation..

Recently, Szulanski (2000) has offered a knowledge transfer process model that applies the main elements of structuration theory specifically to knowledge transfer. In his process model of knowledge transfer, transfer begins with the formation of the transfer seed (initiation), continues with the decision to transfer (implementation), followed by the first day of use (ramp up) and is completed with achievement of satisfactory performance (integration). Factors that affect the opportunity to transfer are more likely to predict difficulty during the initiation phase, whereas factors that affect execution of the transfer are more likely to predict difficulty during the implementation and subsequent phases. Measures of the "stickiness" of knowledge are developed for each stage of the transfer to explore the predictive power of different factors at different phases of the transfer process (Szulanski, 2000).

These studies suggest that a) a knowledge transfer process for innovation should take into account that any artifact being considered for reuse is likely to be adapted during the reuse process, and b) the more adaptable the artifact is (e.g., the more malleable the artifact), the higher the probability of successful reuse.

Research Questions

This review of the literature suggests that the knowledge transfer or re-use process for innovation involves the transfer not just of explicit knowledge but of tacit knowledge as well. Moreover, the process cannot be presumed to always exist, but rather must be triggered. Trigger events include a performance gap or the encouragement of the organization to reuse knowledge

in creative ways. Once the process has been triggered, whether it proceeds smoothly will depend on the presence of several factors, including openness to alternative perspectives, the ability to integrate across different disciplines, common ground between knowledge generators and knowledge reusers, and the compatibility of the knowledge requirements between the task, the people, and the tools. Even when these factors are present, the reuse process will proceed as a series of iterative cycles in which the knowledge being reused as well as the problem being solved by the knowledge is adapted to eventually achieve alignment. This description of the process raises several research questions.

- 1) Is the characterization of the knowledge reuse process for innovation described above reflected by empirical evidence?
- 2) Is the knowledge reuse process for innovation any different than the knowledge reuse process for more routine reuse?
- 3) Are the effects of the above factors on knowledge reuse empirically grounded?

III. METHODOLOGY

We had the opportunity to examine knowledge reuse in an innovation context by examining six cases of innovative reuse across 2 space projects at JPL. The two space projects were labeled MECA and MITCH. MECA was a competitive proposal for NASA and delivery of an instrument package for a space mission. Membership varied depending upon project phased, but averaged a core group of approximately 10 people, with approximately 30 people involved at various points throughout the project. There was a five-month period for proposal activities, followed by a three-year implementation project. The proposal was intended to accomplish the following objectives: To design and implement scientific instruments to analyze the soil and atmosphere on Mars. These objectives had never been accomplished previously; at the time the

RFP (called AO for “Announcement of Opportunity” by NASA) was announced, solutions to how those objectives would be met were not known. MITCH was a proposal for a suite of scientific instruments for NASA that involved 20 of people, working together for 2 months. The proposal was intended to accomplish the following objectives: To design and implement scientific instruments to analyze the soil and atmosphere on Mars. As with MECA, these objectives had never been met previously. These projects have been shelved due to restructuring of the Mars program.

Documents were reviewed for the two projects to identify cases of reuse for innovation. In total, 15 cases were identified as shown in Appendix A. From the cases in this Appendix, we selected six cases for further study. A brief description of these cases is shown in Table I. We obtained data about knowledge transfer and reuse from these six cases. The six cases were selected to represent both adaptive and adoptive reuse. The six cases were then arrayed along a continuum, as shown in Figure I, from "as-is" adoptive reuse, (e.g., the mere adoption of a knowledge generator's knowledge into the project's proposal) to adaptive reuse (e.g., the significant adaptation of one or more pieces of knowledge to create an innovation). Distinctions were based upon the degree of change of form, fit and function. All types of reuse were considered significant, important to the organization, and part of the innovation process. However, we were primarily interested in the adaptive type of reuse, e.g., the type of reuse that leads to new knowledge. Nevertheless, for comparison purposes, we collected data from cases of both adaptive and adoptive reuse.

For each case, a set of key informants was identified. Key informants included the knowledge generators as well as knowledge reusers. Table II indicates the job positions and

roles of each key informant for each case, including whether he was a knowledge reuser, knowledge generator, or participant.

To address our research questions, we developed an interview protocol, which we piloted on one of the team members. The protocol first defined knowledge reuse for the interviewee (the use of an artifact to assist in the development of an innovative process or product. The protocol is shown in Appendix B and included questions about what was reused, how it was reused, and what factors affected the reuse process. Interviews lasted from .5 hours to 3.25 hours (spread over several meetings), with a total of 30.75 hours of interview. Additional questions were sent via email to the informants, the email format is shown in Appendix C. The interviews and subsequent emailed requests for answers to three more questions yielded 103 pages of typed verbatim notes taken during the interviews and from the emails. A breakdown of these figures is shown in Table III.

To analyze the data, the notes for all six cases and additional background information about project management and other cases were organized by each protocol question. Patterns across the cases for each question were noted, including whether the patterns differed for adaptive vs. adoptive reuse cases. The results are displayed in Table IV in which the 6 cases and a seventh column for background and other cases are labeled at the top (with asterisks indicating adaptive reuse cases), the interview protocol questions, 1-16, and the supplemental emailed questions, 17-20, are listed as rows, and the cells describe relevant quotes from the informants.

The intention of this case analysis was not to test hypotheses but simply to inform future hypothesis-development. Therefore, rigorous content analysis was not applied. Instead, patterns in the notes were identified based on extensive discussions between a member of the

team who observed most of the reuse incidents but was neither the reuser nor the knowledge generator in regard to any case). The discussions usually involved the academic authors suggesting certain interpretations of the data and the team member responding that the patterns were too simplistic or inappropriate to explain what happened in the cases. Through this iterative cycles of discussions, a set of patterns that were acceptable to both the industry domain expert and the academic authors finally emerged. While this process does not meet current standards for hypothesis testing, that was not our intent. Our purpose was to explore a knowledge transfer process of which we knew little and to identify a set of hypotheses that could be tested much more systematically. In this sense, then, this was intended as a truly exploratory study.

IV. RESULTS

Based on our analysis of the interview data, nine factors were found to affect knowledge reuse for innovation. The nine factors are:

- project that is experiencing performance gaps
- risk-reduction requirements
- personal openness to examine broad set of knowledge to solve problem
- broad personal knowledgebases that are readily searchable
- team and organizational culture encouraging reuse
- personal interest in the technology or science
- ability to assess credibility and usability of reusable knowledge
- ability to assess degree of fit of reusable knowledge to problem
- ability to assess malleability and implementability of reusable knowledge

The Nine Factors

These factors are displayed in Figure II as a simple variance model and in Figure III as part of a process model of knowledge reuse and in. Each factor as it relates to the six cases is explained briefly below. The factors and relevant quotes from study informants are shown in Table V.

1. Performance gaps

Study participants reported that whether or not they were inclined to consider reusing knowledge was in part stimulated by the existence of a performance gap, i.e., a set of requirements that could not be met by their existing knowledge or the knowledge of the team. For example, in the AFM Tip Array (TIPS) case, the knowledge reuser, a Scientist and Engineer commented on the performance gap that encouraged him to look for existing knowledge that he might be able to reuse:

“They had an operating system of tip arrays that they had developed and had a fabrication process to make them. This is a huge step forward. We immediately knew that we should team up (with the Stanford team) as it would save time and money.”

The Scientist on the Lidar case mentioned an example of concern over budget constraints during our discussion of the availability of the Lidar prototype from the cancelled Champollion project.

As another example, in the Lidar case, the scientist commented that budget constraints stimulated him to look for new solutions, such as the Lidar prototype for the cancelled Champollion project.

“The major problem was the cost cap. Full up development would have broken the bank.”... “(The) key was not the availability of the instrument but the fact that the instrument was in development...”

Table V lists the performance gaps experienced by each of the 6 cases. Apparent from this list in Table V is that performance gaps were expressed in several different ways: as time constraints, as budget constraints, or as challenging performance objectives. The point here is that the existence of the performance gap stimulated the knowledge reuse process by convincing the reuser that existing solutions would not work.

2. Risk reduction requirements

Study participants also mentioned that they were motivated to look for artifacts they could reuse when there was a sense that risk reduction was an important criteria in the evaluation of their work. Historically, the organization had prided itself on producing high-risk outcomes. The Jet Propulsion Laboratory was known for creating innovative solutions for difficult problems. Some of the more innovative solutions may be inherently more risky, or may require more extensive testing in order to have greater assurance of potential successful outcomes. Recently, the organization has undergone pressure to reduce risk, putting heavier weight in the project selection criteria on risk reduction strategies. Study participants reported that this requirement for risk reduction strategies stimulated them to look for knowledge that was reusable. For example, the SCI in the Lidar case commented,

“There was an option to procure an instrument from a sister organization. (This is) a risk management strategy, but funding ramifications would have resulted in the exclusion of certain other instruments from the package. Also, unsure that this would work, as a competing proposal was let out of that center.”

Concerning the design of the Magnetic Patch experimental package, the engineer described the method for reducing risk regarding the expected error in movement of the Robot Arm as it engages the latch,

“(The) latch design solves for limited error of Robot Arm. This is just standard robotics. Latch was double over the center device, standard. (The) arm moves and engages the latch...To close it, it operates in reverse and pushes the plate closed. ...NASA uses these all the time. (The spring is) reasonably protected from dust on Mars, including contamination kicked up on landing.”

While this simple device may not appear an issue of risk to the casual observer, the failure of a latch to engage or disengage may cause the failure of an experiment or even an entire mission.

3. Personal openness to examine a broad set of knowledge resources

Due to a variety of factors, person to person knowledge transfer is often a random process. Often, the larger the organization, the more likely there will be someone with the right

information, but the less likely they will be in your local area (e.g. department or team) (Davenport et al., 1998). We found evidence for this randomness in our cases. For example, one of the engineers at JPL, a knowledge giver who was studying Lidar use in weather detection, had mapped some Lidar views on his sophisticated computer modeling program. Another engineer, working on the Mars robot lander had seen these simulations. He was married to an engineer who was working on the MECA project. She discussed the simulations with the MECA PM who referred the Lidar engineer to the knowledge giver.

When knowledge transfer is limited to random person-to-person encounters, this creates a likelihood that individuals will only reuse knowledge from those with whom the reuser shares physical proximity or from knowledge generators who make themselves readily available to others (Davenport et al., 1998). Such limitations will then constrain the possibilities of reuse, and thus limit the novelty of the innovation.

We found that our reusers countered this tendency to reuse knowledge from only a limited set of knowledge sources by adopting an openness to examining a broad set of knowledge sources to find the needed solution. The PM described his attitude about solving problems in innovate ways:

“We used to be farmers and we are now hunter gatherers”.

The PM explained that what he meant was that, in the past, the scientists and engineers in this organization tended to focus on inventing their own solutions and working with those immediately around them (e.g., "tilling their own soil, borrowing only from the neighbors"). Today, some have adopted a new perspective: if the solution exists somewhere, then we should use that solution rather than invent something that isn't really needed. This perspective fostered a view of their role as not one of tilling their own soil, but of being open to new pockets of

knowledge and a willingness to consider that knowledge before deciding that a solution doesn't exist.

We found that our study participants manifested this openness in several ways. First, they tended to proactively define the problem and their role in the problem in such a way that a limited search of already-known knowledge sources would be insufficient. For example, we found that reusers tended to define problems in such a way that a broad set of knowledge sources could be brought to bear on the problem. That is, instead of defining the problem in terms of "how" the problem should be resolved (such as by assuming what scientific or engineering discipline would provide the solution or pre-defining the set of suppliers most likely to have the solution), the PM defined it by the results they needed to achieve. This ensured that minimum success criteria for the project were clearly specified while allowing for the broadest set of solutions. For example, the reuser in the AFM Design case commented on how he defined the problem:

"The problem was one of finding how to gather non-conducting samples of dirt. (We) ...needed a small package. (We) ...wanted high resolution at a few nanometers well below a micron. (We) ...needed an instrument that didn't require high voltage or a vacuum."

In other words, he did not specify what the instrument should look like.

A second way in which this openness was manifested was that the reusers explicitly did not limit their view of the solutions by traditional boundaries. Such boundaries might be by industry (e.g., a space mission is likely to require only cutting edge technology that is available only in research and development facilities), sector (e.g., a space mission is likely to use only government-supported suppliers), or scientific or technological field (e.g. a space project is unlikely to use any knowledge generated from the electrostatics field). For example, our study participants described people in the organization that would limit the search for solutions to only

government-sponsored suppliers, research and development operations, and space-based scientific and engineering disciplines. In contrast, our study participants were willing to search for solutions in a variety of industries (semi-conductor, vacuum, chemical), sectors (academic, government, commercial) and scientific or technological fields (electrostatics, astrophysics, satellites). For example, the PM was willing to consider the electronics Printed Circuit Board industry as a source for a solution to replacement of tips for the AFM. Others may not have considered this industry, however the PM had previously worked in a wide variety of industries and was therefore well equipped to be an intermediary in a broad social network of scientists and engineers.

A third way in which this openness was manifested was by not searching for point solutions when they looked in their knowledge repositories but instead in searching by analogy. The knowledge reuser in the Electrometer Case was looking for a solution to testing materials for electrostatic buildup. He discussed his search for reusable alternatives when he was trying to figure out how to test for electrostatic buildup on space suits and equipment:

"I worked by analogy. (I) looked around to see what others were doing in the field ... semiconductor industry, electrostatic discharge industry. (There are) a number of companies that deal with clean room garments, chair covers (that require) a minimal static build up. (There was) some help from the textile industry, (for example, an individual) ...from British textile industry."

A final manifestation of this openness was that our reusers recognized that innovation is serendipitous by nature. Thus they functioned during the day by staying attune to opportunities for stimulating their thinking. This often meant seizing unpredictably upon the presence of an artifact or individual to begin a brainstorming process. The MECA project was studying how

the ingestion and inhalation of powdery dust provided a hazard to astronauts. The team felt the solution was grounded in a better understanding of how Mars dust adheres to different materials so they needed to construct an instrument for testing a large variety of substrates for their “stickiness”, with only a small amount of actual Mars dust available to them. The project team was struggling with providing a small sample of powdery dust to the AFM. The PM explains how the “sample wheel” design came about,

“We were in the cafeteria. This prototype is the same size and shape as throw away Styrofoam dessert plates (with a flat bottom and 45-degree sloping sides). Innovation here is if you take an object with a 45 degree slope, when the hole is at the top, it will be horizontal for pouring the dirt in. When it rotates and gets to the bottom, the hole becomes vertical and the excess sloughs off and becomes very close to perfect for looking at the substrates under the microscope. In each of the holes, we put a different substrate. Simple rotation, nothing like this had ever been designed before. We were looking for simplicity. We wanted to build this with only 2 degrees of freedom.”

Thus, the openness to serendipity allowed the team to use a Styrofoam dessert plate encountered during their lunch hour to provide the basis for an innovative design.

4. Broad personal knowledgebases that are readily searchable to find reusable alternatives

An openness to examining a broad set of knowledge sources is of little value if the broad knowledge sources are not readily available and readily searchable. Study participants reported having extensive personal knowledgebases of people, research centers, research papers, suppliers, and physical prototypes. These knowledgebases were personally developed over time based on extensive networking, professional activities, and previous project experience. The knowledgebases were not often electronically organized, ranging from extensive personal

address books to extensive lists of electronic bookmarks, to having a well-articulated network structure indicating who they should call about different kinds of problems. When a new problem arose (as when it was posed by a new client), the potential reuser would draw on that personal knowledgebase to determine who to ask about the different aspects of the problem.

An examination of the knowledgebases used by the study participants indicated that they adhered to Granovetter's (1973) weak-tie theory. Granovetter postulated that distant and infrequent relationships (weak ties) are more efficient for knowledge sharing due to bridging previously unconnected groups and developing broader access to more organizations. Further, the network developed with weak ties is less likely to present redundant knowledge (Granovetter, 1973; Hansen, 1999).

This bridging behavior was noted in a long line of connections through which information flowed in relation to the Electrometer Materials case, in which the problem was one of selecting materials for electrostatic testing that would be found in a space mission, such as space suit fabric, boot materials, glass, plastics and other equipment materials. . One of the scientists on the project team met a knowledge broker from another NASA center at a professional meeting. This intermediary was asked about possible solutions to their problem. While the person did not have the required solution, he did have suggestions of people they might contact. After making that contact, further recommended contacts were offered. Finally, after following the path of recommendations, the right partner with the right solution was identified, a group of scientists who had studied and measured a specific set of materials that could be re-tested by the MECA team. The engineer on the Electrometer Materials case recalls,

“(Some scientists at) Kennedy (Space Center) helped find the materials. Initially I had no idea they had worked in this field. There was someone around, (a scientist, who) was working with MECA on patch plates and he may have had the Kennedy connection.”

When faced with a scientific discipline in which none of the MECA team had experience, team members ventured out to learn about the technology and meet people who could assist them with the design problem. The Engineer on the Electrometer Design case comments,

“Electrostatics is a business. (I) went to a conference and took a short course, half day. I didn’t want to reinvent the wheel.”

This case indicates that, for our study participants, the knowledgebase of weak ties were as valuable as the internet and electronic search tools. The breadth of the knowledgebase was more important than the tools used to search it.

5. Culture of project team and parent organization that encourages reuse

In 1983, Deal and Kennedy studied the renewed interest in organizational culture which they defined as the shared values, rituals, and ceremonies of an organization (Deal & Kennedy, 1983). Kilman (1985) viewed the culture of an organization as analogous to personality in an individual, as a unifying theme providing direction, meaning and mobilization (Kilman & Saston, 1985). We adopt Schein’s formal working definition of culture,

“A pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems.” (1985: 12)

From this definition of culture Schein enumerates three levels of an organization’s culture. The levels commence with the basic underlying assumptions at the unconscious level, to the espoused values level, expressed in strategies and goals and finally to the artifact level, containing the more tangible organizational structures and processes (Schein, 1985).

. A culture encouraging reuse would thus include the set of norms about how people should behave with regard to reuse: are there explicit norms to encourage or discourage reuse?

The scientist participant on the Electrometer Materials case was asked to comment on the organizational culture encouraging reuse and immediately discussed the "not-invented-here" syndrome:

"The NIH syndrome is extreme at JPL. They believe they are world class in everything, and will spend a lot of time reinventing a knowledge base that they could get from collaborating with an outside group. JPL is world class in many things, but not everything. There are not unlimited resources to develop an in-house knowledge base about everything."

The PM had a similar comment:

"Where isn't there not invented here? We have as much hubris as anyone (does) and NIH is rampant. Are we still going to let (supplier) do these things or do it ourselves?"

The PM pointed out, though, that the culture was changing at his organization:

"(NIH) has been tempered, in recent years, by entreaties by (the customer) to partner and ally with other firms and academic. Forced downsizing of JPL gives no option as to whether to partner. You find that you may have better luck outside than inside with certain technologies."

This shift in culture over time appeared to some to be succeeding at reducing the cultural barrier to reuse. For example, the reuser in the Lidar case commented:

"(There is) some hubris. But it doesn't get in the way of acquiring knowledge ...There is a cultural norm of cooperation (compared to) universities (which) are usually competitive"

The engineer in the Electrometer Design case commented:

"There are cultural norms inside NASA to share."

The PI on the MECA project mentioned that,

"At JPL there is a sharing culture, we work hard at it (entertaining, house parties, dinners etc.). ...People are exceptionally ethical. People have trust that their a knowledge won't be misused and then cut loose. People are relaxed."

Thus, while our participants commented that the old culture at their organization discouraged reuse, there had been sufficient a cultural shift for them to believe that reuse was now not only culturally acceptable, but also encouraged.

6. Personal interest in reuse

Previous studies of innovation team members have reported on an interesting enigma. When a team member possesses personal interest or extensive personal experience paired with interest in the problem, the science or the technology, this interest appears to be positively related to “adapt” or “invent” and negatively related to “adopting” an existing technology (Szulanski, 2000). These individuals will expand projects that seem to require a simple “adopt” solution into sophisticated “adapt” projects. “This counterintuitive finding suggests the intriguing hypothesis that a highly motivated recipient can be a double-edged sword in that it may help initiate a transfer but also complicate its implementation” (Szulanski, 2000).(p. #?).

It was noted that most of the participants were excited about the aspect of the project assigned to them. The engineer on the Electrometer Design stated that he was excited about the electrometer project and that this excitement is a key motivator,

“I would not do it otherwise. If I (am) not motivated by the challenge, then I should not undertake the task...learning new things and the challenge of rapid prototyping were the key motivators.”

A scientist on the Lidar case considers other motivation for his interest in the project,

“It was my first involvement in a planetary instrument development...I saw this as an opportunity to advance both the technology and my role.”

However, both the reuser and the PM on the AFM Tip Array case were excited during the development and design, but when it came to implementation they were pleased to allow the implementation partner to take charge of the Tip Array manufacture. Similar results were found with adoption of the Pathfinder experiments in the Magnetic Patch case. The engineer and

scientist centered their adaptive work on those technologies that interested them (e.g. deployment mechanisms and unique device to hold the materials) and adopted other technologies (e.g. materials selection from Kennedy Space Center and the magnetic patch experiments from Mars Pathfinder)

7. Ability to quickly assess the credibility, utility and feasibility of potentially reusable knowledge

A reuser in the case AFM Tip Array case noted that when contacting the potential partner, "We knew his reputation, and thus, trusted his designs".

In the Electrometer Materials case, the project team worked with partner with whom they had no previous working relationship. In the words of the knowledge reuser,

"We worked with the people at Kennedy Space Center to design the electrometer experiments on various materials. While working with the data was important, it was equally if not more important to have a lot of discussions and meetings. This was more about building relationships (than about testing materials)."

Another reuser in that same case mentioned why they went with the partner. According to the reuser, the partner had well known in the field of materials testing:

"Number one reason was that these were recommended and it developed our credibility by using their credibility."

Clearly, then, an ability to quickly assess the credibility of the knowledge generators was critical to the reuse process. Credibility was often assessed through reputation, through human interactions to assess the confidence and validity of the data on which judgments were based, and by examining concrete artifacts. Frequent comparison between the model or "template" or artifact and the replica being created, entailing exchanges of information between the source of the knowledge and the receiver assisted in the process of transfer (Nelson et al., 1982; Szulanski, 2000). The reuser in the Electrometer, for example, purchased a commercial off-the-shelf electrometer in order to assess its testing properties:

"Then, upon meeting with the electrostatic specialists at (the partner firm), I observed a large measurement apparatus. I had the idea of combining the electrometer with the insulators as integral to the instrument. When I saw Gompf's machine it was a physical proof of concept."

In the Magnetic Patches case, the reuser noted,

"(The) surface of the patch plate was the same as that used on Pathfinder, magnesium material, bead blasted with a specific process and then platinum plated and carefully handled...(We) used (the knowledge giver's) handling instructions and bead blasting instructions."

8. Ability to quickly assess the degree of fit of potentially reusable knowledge.

The PM pointed out the difficulty of using existing products:

"You cannot use just any machine on Mars. For example, you cannot use your laptop computer on Mars. There may be problems of radiation, hardness of chips, resistance to shock and vibration, resistance to dust. You usually have to invent the hardware from scratch."

Thus, to reuse existing knowledge requires a very clear concept of the performance targets and then determining the extent to which the potentially reusable knowledge currently fits (or can be modified to fit) those targets. For example, the reuser in the AFM case the scientist/engineer was able to identify several possible existing solutions to his problem of what type of microscopy hardware to use. However, upon further examination, only the AFM met the tight performance requirements that would allow viewing of non-conducting particles of dirt, below one micron in size. He discusses the team's assessment of fit:

"We know that the basic requirements (to operate an) AFM are quite modest. You can run it in air (vs. vacuum) and you don't have to do much preparation. You can get the head compact and good package to fly. We had experience with getting SEM (the other option) qualified for space and it had not been qualified up to now. Thus we saw the benefits of using the AFM over the SEM. (We) thought briefly of the scanning tunneling (microscope, the third option) , but you must have a conducting sample and this type of sample is not expected on Mars."

The study participants reported that an ability to make these fit assessments was often critical to whether existing knowledge solutions would be re-used since each participant had very

large and broad knowledgebases to search. They needed to apply quick scanning techniques to their searches in order to determine useful alternatives within the project or proposal schedule.

In the case of the AFM Tip Arrays for example, the reuser assessed fit by calling a well-known professor to find out what he was doing in the field of scanning tips for semi-conductors.

“I talked to (the professor)’s post-graduate student via telephone and he mentioned that they were working on tip arrays. I checked their website for downloaded specifications and pictures of the array. We then invited the professor into a teleconference of the MECA proposal team. I then went up there to meet him while I was seeing other people in the Bay area.”

This all occurred in a few weeks time, and helped with the assessment of the usefulness of the knowledge.

9. Ability to quickly determine the degree of malleability of the reusable alternatives.

The final consideration in the assessment of reusable alternatives is the malleability of design for performance. The ability to rapidly identify whether each problem with fit can be overcome will assist in this process. Opportunities to rectify unexpected problems may occur and satisfactory performance levels can be achieved with assistance from the source. In the Magnetic Patches case, the knowledge giver transferred the experimental concept, procedure and the calibration of materials. The engineer noted that the he was also an active participant,

(The knowledge giver) critiqued the design based on his experience on the Mars Polar Lander and Mars Pathfinder. He participated in every aspect of the experiment.

Another aspect of malleability is the determination if adaptation to an alternative has been moving in the right direction in relationship to performance and other critical success criteria. For example, the electrometer assembly in the Electrometer Design case needed to be extremely compact to fit within the scoop of the robot arm. The MECA engineer had produced several iterations of a design that began to yield smaller and smaller packages, although the

performance criteria had not yet been met, the trajectory of improvements in the design were in the right direction. It was likely that the miniaturization would be adequate by the time the instrument was assembled. The engineer turned out to be correct in his assessment:

"By the time the last prototype was built all six instruments (electrometers) fit into the heel of the scoop."

A final element in determination of malleability is the question of plausibility of implementation. Several questions form part of this problem; 1) is implementation possible, 2) is assistance available (from the source, from the inventor, from the manufacturer), 3) are the required models, prototypes, specifications and data available and are these sufficiently transparent for rapid modification? For example, in the case of the Lidar, the prototype was available and could be modified for the intended use with the assistance of a Canadian partner and the Canadian Space Agency who had designed it for the Champollion project.

"While the prototype is tangible, the intended application was somewhat different. The original device (was designed) to measure echoes from the surface. We were using it to measure the echoes from the particles in the air...The laser was borderline for this application. Change was needed to increase substantially the laser performance at the expense of the pulse rate. Reducing the pulse rate was permissible ...our application did not demand such a high density of pulses."

In the case of the Electrometer Materials and the Magnetic Patches cases, the partner was willing to provide the materials that had been pre-tested for space as well as the test data. The machine that measured the electrostatic properties was a "proof of concept", according to the reuser, where the design was adaptable, after miniaturization, to the MECA project.

In the case of the AFM, the project team has to switch manufacturers twice. The final fabricator worked well with the MECA team.

Summary of Variance Model

Examining the nine factors that were found to affect knowledge reuse for innovation indicates that the factors can be grouped into more abstract (and thus generalizable) sets of factors. These sets include those factors associated with:

- task (e.g., performance gaps and risk reduction requirements),
- individual abilities (personal openness, broad personal knowledgebase),
- organization's integrative capacity (e.g., culture encouraging reuse),
- how the potentially reusable knowledge is captured, displayed, and interacted with (e.g., ability to assess credibility, degree of fit, malleability, and implementability of knowledge), and
- individual's personal motivation for reuse (e.g., personal interest in reuse)

The correspondence of this more general set of factors to the literature cited at the beginning of this paper is readily apparent. The knowledge creation and organizational learning described triggers the reuse process as being grounded in a real performance-based need. We found that scientists and engineers were more likely to reuse knowledge when there was a real performance gap and risk reduction requirement that could not be solved through pure invention. The resource-based view of the firm espouses the need for firms to foster both individual functional ability as well as the ability to integrate across individual functions. We found that scientists and engineers were more likely to reuse knowledge when they had the personal ability to do so (by having an openness as well as a broad personal knowledgebase to search) as well as the organizational norms (as in culture) to do so. Finally, just as the knowledge creation and common ground models suggest that both tacit and explicit knowledge must be transferred, we found that we were able to identify the components of this knowledge that needed to be transferred - components that represented both tacit and explicit knowledge. These components

included information that would allow a potential knowledge reuser to assess the credibility, usability, and degree of fit, malleability, and implementability of the knowledge being considered for reuse. Our more general model of these 6 abstracted factors is presented in Figure II.

Our results are similar to those found in a recent study by Busby and Lloyd (1999) on the reasons for failures in engineering design reuse. In their research, Busby and Lloyd found that designs were not reused because designers had attitudes that were inimical to reuse including associating self-esteem with invention and a bias against a particular individual's design due to past experience (Busby & Lloyd, 1999). This would be equivalent to our factor of Openness to Examine Broad set of Knowledge. Busby & Lloyd found that another factor contributing to reuse failure was the lack of fit of previous solutions to the new performance requirements; for example, a desire to reduce production costs led to less reuse because previous designs were generally more complex and costly to produce than new designs. Finally, they found that the malleability of the potentially reusable knowledge was often so poor that creating new designs was easier (Busby et al., 1999).

While our six abstracted factors have grounding in the existing literature, they go beyond the existing literature in one important way. How the factors were actually used in the six cases showed differential effect depending on whether the knowledge being reused is adopted vs. adapted. For example, a performance gap is more likely to encourage adoptive reuse rather than adaptive reuse, provided an adoptive solution can be easily found. However, a personal interest in generating a creative solution to that particular problem (rather than simply applying a known solution) will encourage adaptive solutions, rather than adoptive ones. This suggests then that

the distinction between adoptive and adaptive reuse is an important one since it affects the knowledge transfer model used.

Process-based Model

In addition to the variance model listing factors that may affect the likelihood of reuse occurring, our detailed case analysis allowed us to suggest a model of how the knowledge transfer model unfolded over time. The model is displayed in Figure III. As shown in Figure III, knowledge reuse is triggered by the need to identify alternative design solutions to meet a set of project requirements. If an immediate search of the designer's broad personal knowledgebase indicates an existing solution that is credible, usable, fits with project requirements, and implementable, then that solution will be readily adopted. However, if the search indicates that existing solutions still leave an unresolved performance gaps and risks, then the designer must engage in a more proactive search for solution. If the designer prefers to invent rather than reuse, if the project's task definition encourages invention, and if the organization's culture permits or encourages personal invention, then reuse - even of the adaptive kind - is unlikely to happen. However, if the inverse of these conditions exists, and the individual has a broad knowledgebase available to him, then adaptation becomes a feasible option. Adaptation will only occur, however, if the designer can readily assess the credibility, usability, degree of fit, malleability, and implementability of various design alternatives. These assessments are typically made by directly interacting with the knowledge generator; however, they could be made by interacting with the knowledgebase itself, if the knowledge and interface were structured appropriately.

The MECA instrument project is used here to illustrate how the process unfolded. The first step is the examination of project alternatives. According to the Project Leader for the MECA instrument package project,

“We wanted to know about the soil and dust on Mars, the toxic components, electrostatic properties, size and shape of particles. (The) important thing is how do particles find their way into your environment. No one is outside taking a breath of air. How does dust interacts with the human environment? It tracks in on suits, machines. What will be attracted to fabric, materials, etc? How do you prepare a field of view that does not have too much dust? How do you study the particles and how they stick and to what?”

Thus, the project requirements encouraged the PM to begin to examine alternatives.

In the next phase, alternatives are identified. The process is triggered by the perception of a performance gap between existing solutions and an optimal solution and risk reduction requirements. Selection of alternatives are affected by the culture of the organization and the personal interest in the technology of the participants. We noted that the identification of alternatives in the MECA project used the broad personal knowledgebases and openness of the participants. This finding was confirmed by several comments including the following comment by the PM,

“These microscopes are tools. The problem (is that) of looking at particles. Each of us had different instrument specialties. What drew me in was my expertise with the Scan Probe Microscope (SPM) which includes a specific type of SPM, the Atomic Force Microscope (AFM). Another type of SPM is the Scanning Tunneling Microscope (STM), there are also thermal (microscopes) and others.”

Having identified the alternatives, the reuser must be able to quickly assess each alternative. In the MECA project, this was noted through the assessment of credibility, usability, degree of fit, malleability and implementability (factors 7 through 9). These factors have been discussed earlier. However it is important to note that there are special considerations for space missions that make knowledge reuse more difficult, as discussed by the PM,

“You cannot use just any machine on Mars. For example, you cannot use your laptop computer on Mars. There may be (special) problems of radiation, hardness of chips, resistance to shock and vibration, resistance to dust. You usually have to invent the hardware from scratch.”

If a reusable solution is found, based on the reuser's evaluation, the alternative under consideration for reuse may either be adopted "as-is", adapted, or not reused. In the MECA project, the team was able to adopt most of the technology from Pathfinder and Mars Polar Lander for the Magnetic Patches and for the materials used in the Electrometer and Magnetic Patches experiments. However, extreme adaptation was necessary for both the Lidar and the Electrometer Design. In addition, the special needs of high quality and longevity of the final product are also major design considerations. These were discussed by the reuser in the Magnetic Patches case,

“When you design something that can't be serviced later, it is very different than anything that is done anywhere else on the planet. To be able to do engineering that has no mistakes is not really taught in engineering schools (except for the design of pacemakers and atom bombs). JPL specializes in making things work for long periods of time in hazardous environments.”

It should be understood that the reuse process is not an island. During the development and implementation phases, this process may be revisited again if it is determined that the chosen alternative will not be suitable due to cost, time, performance, availability of suitable expertise or partners for the solution chosen.

There are several elements of this process model that we believe goes beyond existing models, such as that suggested by Nonaka (1995), Szulanski (2000), and Von Krogh (2000). First, the model suggests that reusers may choose not to reuse, to adopt, or to adapt at any point in the knowledge transfer process. Their choices are based on information that they are continuously gathering and the assessments they are making about the knowledge itself, and how the knowledge fits their problem. Thus, rather than viewing the knowledge transfer as a

sequential flow process, it is much more like an emergent knowledge process (Markus, Majchrzak, & Gasser, 2000) - one in which bits of knowledge are being related with other bits of knowledge and synthesized to a final decision. Second, the model suggests that re-users adapt the knowledge, even as they are deciding whether or not they might want to adopt, adapt or discard the knowledge. That is, by assessing the credibility, usability, degree of fit, malleability, and implementability of the knowledge, the reusers are likely to be eliciting additional information about the knowledge, which in turn alters the knowledge. Thus, as pointed out by Weick (1995), Brown & Duguid (1998), Hutchins (REF?), and others, knowledge is not an objective reality but rather a subjective interpretation of data that will change as new data is brought to bear (Brown et al., 1998; Weick, 1995). Finally, the model suggests key leverage points for when and how to encourage reuse. These leverage points are such that knowledge reuse can be encouraged during any of the three processes.

When alternatives are being identified (at which point broadening out personal knowledgebases is valuable), when alternatives are being assessed (at which point, providing the information necessary to make assessments is valuable), and again when the reuse is selected and needs to be implemented (at which point, the expertise, interest and cooperation of the parties is valuable).

IV CONCLUSIONS

This research has three implications. First, this research suggests a number of hypotheses that warrant testing about knowledge reuse in innovation.

Hypothesis 1. The experience of performance gaps in the project, including time criticality of the project, cost limitations of the project, and performance requirements where reuse would assist in the project's positive outcome will be positively related to knowledge reuse.

Hypothesis 2. Where reuse can fulfill risk reduction requirements it will be positively related to knowledge reuse.

Hypothesis 3. Team members' personal openness to knowledge reuse will be positively related to knowledge reuse.

Hypothesis 4. Team members' broad personal knowledgebases and active knowledge searching to find reusable alternatives will be positively related to knowledge reuse

Hypothesis 5. The culture of the project team and parent organization that includes trust and encourages knowledge sharing and reuse will be positively related to knowledge reuse.

Hypothesis 6. Team member's interest in the specific technology, scientific discipline, product or process to be developed will be positively related to adapt or invent and negatively related to adopt.

Hypothesis 7. Team members' ability to quickly assess the credibility of a source, the utility and feasibility of the knowledge and reusable alternatives will be positively related to knowledge reuse.

Hypothesis 8. Team members' ability to quickly assess the degree of fit of the reusable alternatives will be positively related to knowledge reuse.

Hypothesis 9. Team member's ability to quickly determine the degree of malleability of the reusable alternatives will be positively related to knowledge reuse.

To test these hypotheses, we propose a survey of 150 - 200 engineers, technologists and project managers at the Jet Propulsion Laboratory regarding reuse cases on projects within the last 24 months. In addition, we propose in depth, face to face interviews of approximately 15% of the subjects of the study. These interviews will provide depth and greater understanding of how the knowledge reuse process takes place at the Jet Propulsion Laboratory. Additional future research should center upon a selection of 15-20 firms involved in innovative projects to test whether the process and variance models can be generalized to a larger population.

A second implication of this study is for theories of knowledge management. Our research suggests that knowledge reuse research should spend less time debating whether tacit versus explicit knowledge is required for knowledge transfer and more time on articulating what might be the attributes of the knowledge that need to be articulated (whether explicitly or tacitly) for knowledge transfer to occur. Moreover, while our research provides evidence for several factors listed in the literature as affecting knowledge reuse, the fact that the factors differed

depending on whether reuse is for adaptive vs. adoptive reasons suggests that this is a critical distinction that should no longer be ignored.

A final implication of our research is on the design of knowledge management systems. We have found that knowledge is transferred, adapted, and synthesized with other knowledge as part of the innovation process. What we haven't explored is the role of knowledge management systems in this process. All six cases primarily relied on human-to-human contact for the knowledge to be transferred, adapted, and synthesized. Such manual techniques are sufficient as long as the collocation and reliance on who you know will yield the innovative leaps required. Increasingly, however, problems are becoming more complicated; as a result, innovative leaps are coming from the integration across disparate knowledgebases. Often, no one person can possibly have knowledge in all of the related areas. This is where technology needs to enable the process. We have suggested some initial requirements for such a technology: it should have a broad enough knowledgebase and have proactive search techniques to allow unexpected connections to be made; and it should enable quick assessments of the credibility, usability, degree of fit, malleability, and implementability of various alternatives through rapid prototyping, simulations, querying, and modeling. We have also suggested some initial organizational requirements for such a knowledge management system: the organization must have the organizational culture to encourage reuse, hire employees with an openness for reuse and interest for reuse, and create a sense of urgency in which performance gaps and risks will be unsatisfactorily resolved without reuse.

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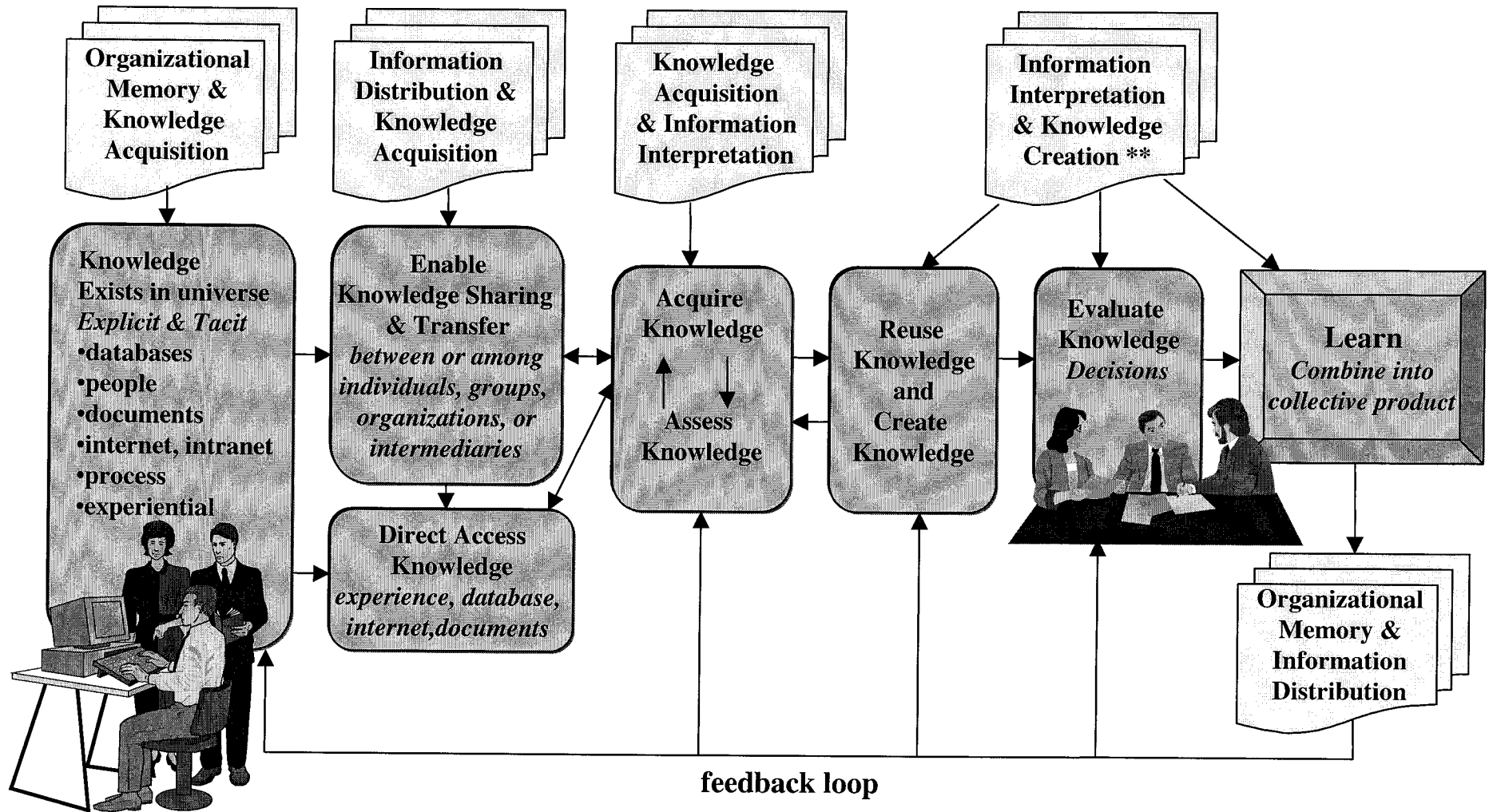
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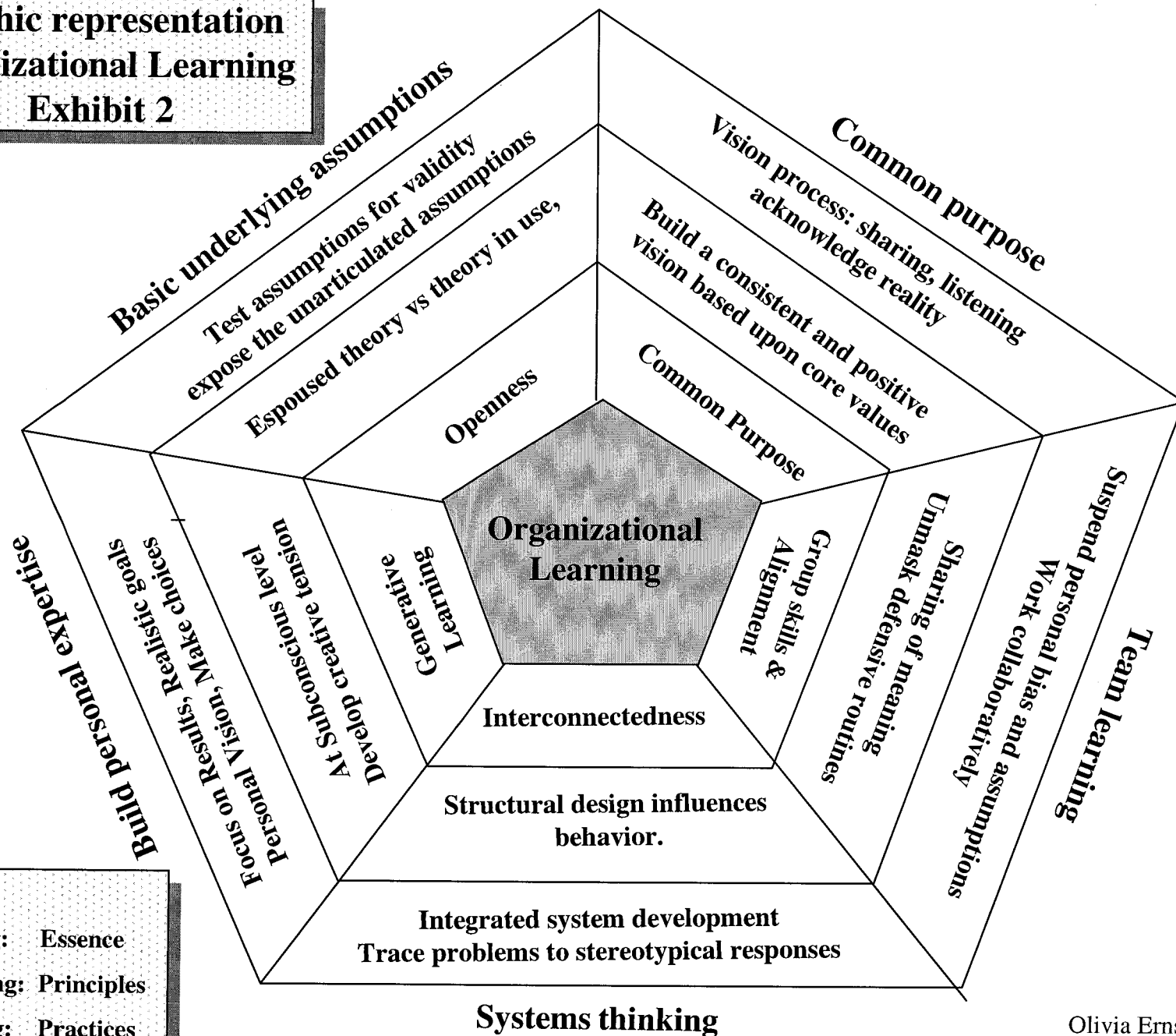
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Five Organizational Learning Literature Constructs* & the Learning Process

Exhibit 1



**Graphic representation
Organizational Learning
Exhibit 2**



LEGEND:

Inner Ring: Essence

Middle Ring: Principles

Outer Ring: Practices

Olivia Ernst Neece
11/2/2000

TABLE I
Knowledge Reuse: Brief Description of Six Key Cases

Case	Description
AFM Design (AFM-D)	Adoption of an atomic force microscope (AFM) used in the semi-conductor industry to test surface smoothness, to be used on Mars to characterize particles.
AFM Tip Array (TIPS)	Adaptation of technology concept to use multiple AFM tips to increase scan speed in semi-conductor industry, to instead provide redundancy for operation on Mars through reusable tips for AFM.
Electrometer Design (EL-D)	Adaptation of industrial electrometer for use on Mars by combining rubbing and measuring functions in one instrument to test the electrostatic properties of materials for equipment and space suits
Electrometer Materials (EL-M)	Adoption of existing set of materials from Kennedy Space Center collection for use in electrometer. Actual materials as well as test data were available
Lidar (LID)	Adaptation of Laser Radar (Lidar) from previous mission where it was used for hazard avoidance to use on surface of Mars to detect dust devils.
Magnetic Patches (MAG)	Adoption of previous Mars magnetic experiment on materials, to fit into new Mars mission in different size package.

TABLE II
Knowledge Reuse: Key Informants for Six Key cases

Case	Informants	Informant's Role
AFM Design (AFM-D)	PM SCI/ENG	KG, KR KG, KR
AFM Tip Array (TIPS)	PM SCI/ENG	KR KR
Electrometer Design (EL-D)	PM SCI ENG	KR KG KR
Electrometer Materials (EL-M)	PM SCI ENG	KR KG KR
Lidar (LID)	PM SCI ENG	KR KG, KR PA
Magnetic Patches (MAG)	SCI ENG ENG	KG KR PA

Informants

PM = Project Manager

SCI = Scientist

ENG = Engineer

Note: Some informants played dual roles

Informant Roles

KG = Knowledge Giver

KR = Knowledge Reuser

PA = Participant

TABLE III
Knowledge Reuse: Interview Data Collection Data

Informant	Date(s)	Case(s)	Hours	Transcript pages
ENG	3/1/2000	Background: all cases	2.25	6
ENG	4/10/2000	Background, Interview protocol, multiple cases, project discussion	2.75	8
SCI/ENG	4/10/2000	AFM Design, AFM Tip Array	1.0	7
PI	4/13/2000	CCDs & Project Management	2.0	6
SCI	4/17/2000	Lidar	2.0	8
PM	4/20/2000	Background: AFM, Chemistry, Electrometer & Patch Plates	1.75	4
SCI/ENG	5/01/2000	AFM Design, AFM Tip Array	2.25	7
PM	5/01/2000	Electrometer Design & Materials	2.0	6
ENG	5/18/2000	Electrometer Design & Materials General discussion	1.0	1
SCI	5/22/2000	Electrometer Design & Materials	2.75	8
ENG	6/1/2000	Electrometer Design & Materials	1.75	5
PM	6/8/2000	Lidar	2.5	7
PM	6/11/2000	Project discussion	.5	1
ENG	11/20/2000	Magnetic Patches	3.0	8
SCI	11/29/2000	Magnetic Patches	3.25	8
PM	12/17/2000	AFM Design, AFM Tip Arrays, Electrometer, Electrometer Materials	-	5
SCI/ENG	12/17/2000	AFM Design, AFM Tip Arrays	-	3
SCI	12/18/2000	Lidar	-	2
ENG	12/20/2000	Electrometer Design, Electrometer Materials	-	5
ENG	--	Magnetic Patches	-	2 (approx)
SCI	--	Magnetic Patches	-	2 (approx)
		TOTALS	30.75 Hrs.	109

APPENDIX A

Knowledge Reuse: Description of the Projects and Cases studied at the Jet Propulsion Laboratory

Overview of Projects:

The cases studied for this research were drawn from two projects at the Jet Propulsion Laboratory. Both projects developed proposals for the design and implementation of scientific instruments to analyze the soil and atmosphere on Mars. For Project A, the proposal period lasted approximately 5 months. The proposal was selected via a competitive process, and the project which successfully developed the instrument ran from December 1997-September 2000. For Project B, the proposal period lasted approximately 2 months. The proposal was partially selected via a competitive process, but due to external circumstances was not implemented. These projects were chosen because they each contained several examples of reuse and the participant-observer had a significant role on, and therefore significant insight into, each of them. The cases were limited to examples of the reuse of technical or technology information, rather than management information (e.g., cost, schedule, planning) or administrative information (e.g., documentation)

Both teams were composed of a Proposal/Project Manager, science investigators, and engineers. The science investigators were responsible for designing the scientific experiments and ensuring that valuable data would be collected. The engineers were responsible for designing and implementing the instruments to carry out the experiments and ensuring that those instruments worked. The proposal/project manager was responsible for the overall concept, managing the team, and completion of the project. There was some overlap in membership between the teams from Projects A and B.

Case Descriptions:

The cases consisted of a single instance of reuse from either Project A or Project B.

Case 1: Atomic Force Microscope (AFM) Design

Project: A

Adapt/Adopt: Mid-Level Adopt

Timeframe: Proposal (5 months)

Description: An Atomic Force Microscope (AFM) is an instrument for looking at surfaces with nanometer resolution. It consists of a tip at the end of a cantilever. The tip scans the contour of a surface using piezoelectric forces to measure the physical height. An AFM produces a set of height data (a "scan") that can be used to create a 3-D model of a surface.

Innovation: AFMs are used in the semi-conductor industry to test the surface of wafers for smoothness and detect any imperfections. Project A adapted the AFM to examine particles that were intentionally placed on a smooth surface. While the basic operation of the AFM remained the same, the function changed from detecting sporadic imperfections to characterizing particles in a large sample of soil. The design had to be modified to fit size, mass, and space-environment requirements (Mars-gravity, cold temperature, and vacuum/partial air pressure).

Knowledge Generator: Project manager and Scientist/Engineer had built up an extensive working knowledge of AFMs through laboratory experiments using the AFM for its original use. They had access to extensive equipment documentation, academic papers and research notes, and they had hands-on experience using the equipment.

Knowledge Reuser: Project manager and Scientist/Engineer used their experiences and associated knowledge base to conceptualize the AFM as a particle analyzer and adapt it for use on the surface of Mars.

Informants: Scientist/Engineer = Co-Investigator & Cognizant Engineer, MECA Microscopy
Project Manager = Proposal Manager/Project Manager, MECA

Case 2: Atomic Force Microscope (AFM) Tip Arrays

Project: A

Adapt/Adopt: Mid-Level Adapt

Timeframe: Proposal (5 months)

Description: The use of AFMs to detect imperfections on surfaces which are expected to be smooth means that finding a particle is expected to be a rare occurrence. Project A's use of the AFM to characterize particles, however, means that the tip will constantly be exposed to irregular surfaces and thus is prone to wearing out (or getting dirty as particles stick to it).

Innovation: Project A therefore had to come up with a way to perform a relatively large number of particle scans. A team at Stanford University had developed a way to array a set of AFM tips. The purpose of this array was to speed up the scanning of smooth surfaces. The tips were arranged in a line and the entire set of tips were scanned over adjacent sections of the surface simultaneously. Project A adapted this concept to create an array of tips – but only one tip would be used at a time. Each tip was set next to its neighbor, but set back a distance (so the array appeared to be a diagonal line). The front-most tip would be used until it was no longer operational. Then it would be broken off and the next tip would be used. Therefore, instead of using the Stanford tip array concept for parallel scanning, it was adapted to provide redundancy

Knowledge Generator: The team at Stanford University developed the arraying technique. They had information set up on their website showing the use of the array.

Knowledge Reuser: Scientist/Engineer and Project Manager used personal contacts, web-based information, and reports to learn about the Stanford work.

Informants: Scientist/Engineer = Co-Investigator & Cognizant Engineer, MECA Microscopy
Project Manager = Proposal Manager/Project Manager, MECA

Case 3: Electrometer Design

Project: A

Adapt/Adopt: High-Level Adapt

Timeframe: Proposal (5 months)

Description: An electrometer is used to measure triboelectric charging, which is where two materials rub together and exchange ions, resulting in buildup of charge. Electrometers are used in a variety of industries for earth-bound application (e.g., textiles, utilities). The Project A electrometer was used to examine electric properties of Martian soil, dust, and atmosphere. It was placed at the end of the Robot Arm (which extended from the deck of the 2001 Lander and could reach down to touch or dig in the soil) to be brought into contact with different substances on the surface of Mars.

Innovation: The electrometer design is based on designs found in many routine industrial applications. For these applications, two materials are rubbed together and the electrometer is brought in to read the charging. On the surface of Mars, the material whose properties are being measured is the dust or soil, and the challenge was incorporating a second material with known properties to rub against the soil. Project A solved this challenge by incorporating the rubbing material into the sensor assembly so that the rubbing and measuring takes place at the same time with an array of materials, thereby combining two functions into one unit. The instrument was then miniaturized, electronics chosen that could handle the extreme temperatures, and the entire thing packaged to fit within an extremely small volume. The electrometer innovations were in form (array of sensors), fit (into the heel of the robot arm scoop), and function (rubbing and measuring).

Knowledge Generator: Industrial electrometers existed and were available commercially. Numerous resources were available to provide insight into the theory behind the measurements and how the existing instruments worked. In addition, a cadre of personnel at the Kennedy Space Center had substantial experience with using electrometers in the testing of various materials.

Knowledge Reuser: Engineer used web/catalogue searches, professional society literature and conferences, and commercial product documentation to learn about electrometers. Personal contacts were facilitated and resulted in a collaborative effort with personnel from Kennedy Space Center.

Informants: Engineer = Cognizant Engineer, MECA Electrometer
Scientist = Co-Investigator, MECA Patch Plate
Project Manager = Proposal Manager/Project Manager, MECA

Case 4: Electrometer Materials Selection

Project: A

Adapt/Adopt: Low-Level Adopt

Timeframe: Proposal (5 months)

Description: The electrometer innovation described in Case 3 required that a set of materials be selected for integration into the electrometer instrument. The selection of these materials had to satisfy three primary concerns: (1) they had to provide valid, able-to-be-calibrated scientific data, (2) they had to represent materials that would be used as part of future human exploration of Mars, and (3) they had to meet strict planetary protection requirements (since these materials would be brought into direct contact with the Martian environment).

Innovation: The primary innovation took place in the design of the electrometer to integrate these materials into the instrument (Case 3). A second aspect of re-use was in the selection of the materials. The team at Kennedy Space Center had assembled a vast collection of materials, documentation, test data, and analysis results for the potential materials (hundreds of candidates). They used their expertise with both the materials -- and how these materials are used in space exploration -- to recommend a set of materials for use in the electrometer.

Knowledge Generator: The cadre of personnel at the Kennedy Space Center had a substantial knowledge base regarding materials, their electrostatic properties, and their potential for use in space exploration.

Knowledge Reuser: The Electrometer team made use of the Kennedy Space Center knowledge base in making the final selection of materials and defining the experiment. Primary interactions were between Engineer (JPL) and Engineer (KSC). In addition to interpersonal communication via telecons, email, and face-to-face meetings, documentation and sample materials were exchanged, test equipment was borrowed/used, and people collaborated on the analysis and interpretation of data. The

Kennedy personnel were provided with their own copy of an engineering model of the electrometer to use in their test environment to evaluate materials.

Informants: Engineer = Cognizant Engineer, MECA Electrometer
Scientist = Co-Investigator, MECA Patch Plate
Project Manager = Proposal Manager/Project Manager, MECA

Case 5: Laser Radar (Lidar)

Project: B

Adapt/Adopt: High-Level Adapt

Timeframe: Proposal (2 months)

Description: The Lidar was proposed in Project B as a means of detecting dust devils on the surface of Mars. The Lidar would use a laser to scan the horizon, measuring airborne particles. A pattern indicative of a dust devil would trigger a camera to take a picture.

Innovation: The Project B Lidar was adapted from a prototype Lidar designed for the Champollion spacecraft. There was a significant change in the function of the Lidar from a downward-looking Lidar used to identify and avoid hazards to a horizon-looking Lidar used to detect weather phenomenon. There was also a significant difference in operating environment (descent imaging on a comet vs. operating on the surface of Mars) and the need to greatly reduce the size, weight, and power consumption. By combining the Lidar with an existing camera system and using the camera mount to provide the scan capability, Project B was able to change the form of the Lidar to fit the project constraints. There were also smaller adjustments in the wavelength of the laser and the control algorithms.

Since this required a major development effort which would have taken most of the MITCH budget, an alternative partnership was investigated. One of the two Champollion Lidar prototypes was built by a Canadian company, Optech. Since the Announcement of Opportunity from NASA indicated that the Canadian Space Agency would be willing to fund a Robot Arm for the Mars Surveyor 2003 Lander, the CSA was approached by the MITCH team to see if they might be willing to fund the Lidar development instead. Therefore, in addition to reusing and adapting the technology, MITCH also reused and adapted the partnership.

Knowledge Generator: The knowledge which led to this highly innovative and complex system design came from several sources. There was a precedent for using Lidar on Mars because the [ill-fated] Mars Polar Lander included a sky-looking Lidar to study clouds. This Lidar, however, was provided by the Russians as an experiment and at this time the Russian space program was near collapse and a partnership highly unlikely. Detailed documentation on the Russian design was limited, but its existence and intended use was highly publicized.

The primary knowledge source was the Champollion prototype. Actual hardware existed and had been used in a series of tests at JPL, which resulted in an impressive data set. Various groups involved in the Champollion effort had design and integration information, detailed descriptions of the underlying principles for how the Lidar worked, and confidence in both the skill and willingness of the Canadian company developing the Lidar to deliver a quality instrument.

The Announcement of Opportunity (AO), which is the NASA science equivalent of a Request for Proposal provided detailed information on the Canadian Space Agency's willingness to participate in the overall mission (and therefore provide capabilities of use to the proposers of individual instruments). Although this participation was for a robot arm rather than a Lidar, the information on

points of contact and parameters of CSA participation provided valuable information that led to a NASA-CSA agreement. This information was published on the web.

Knowledge Reuser: Project Manager came up with the concept of using a Lidar for dust devil detection. He used personal contacts to get information on the Champollion effort and to enroll Scientist (JPL) in the team. Personal contacts from Cooper enabled the team to see a data set resulting from an trial use of the prototype. The information in the AO on the CSA participation served as the starting point for a series of personal contacts to negotiate a partnership. Tratt had extensive personal background in the area of Lidars and worked detailed design issues. This was such a complicated instrument to propose that several threads of knowledge all had to come together to make it feasible.

Informants: Scientist =Co-Investigator, MITCH Lidar
Project Manager = MITCH Proposal Manager
Engi;neer = MITCH Proposal, Volume 2 Manager

Case 6: CCD Use

Project: A

Adapt/Adopt: Low-Level Adopt

Timeframe: Proposal (5 months)

Description: An optical microscope was proposed by Project A to examine the size and shape of soil particles on Mars. A charge coupled device (CCD) was needed to capture the image viewed through the microscope optics and convert it into an electrical signal. The CCD consists of two parts: (1) the actual array of detectors, commonly referred to as the CCD, and (2) the electronics which read the values on the detectors and convert them into digital data. Both parts are needed and generally the detectors and electronics need to be developed together.

Innovation: Project A had serious mass constraints and needed to identify solutions that would reduce mass, as well as development costs and schedule. The innovative solution for the CCD was to realize that a similar CCD that was suitable for this application was being used on another instrument and it was possible to share the read-out electronics between the two instruments since they would never be operating simultaneously. By using a copy of the other instrument's CCD, Project A was able to eliminate the mass of a second set of electronics and use the previously developed CCD design. This effort used the same form and function and made only slight modifications to the fit of the CCD.

Knowledge Generator: The CCD was developed for the other instrument (the Robot Arm Camera) by the University of Arizona. They had used similar CCDs in cameras for the Mars Pathfinder and Mars Polar Lander missions. Detailed design data, performance data, and confidence in being able to operate in the Martian environment were provided by the developer.

Knowledge Reuser: Project manager recruited the leader of the University of Arizona effort to be part of the team. Exchange of information was interpersonal, but also included written papers, press releases, and technical documentation on previous applications of the technology.

Informants: Principal Investigator = Principal Investigator, MECA
Project Manager = Proposal Manager/Project Manager, MECA
Engineer = MECA Instruments Cognizant Engineer

Case 7: Magnetic Patches Use

Project: A

Adapt/Adopt: Low-Level Adopt

Timeframe: Project critical design (6 months)

Description: The patch plate experiment consists of a metal frame with slots (roughly 1 cm in diameter and 1 cm deep) for materials and nano-experiments. The patch plate is a passive instrument that once opened is exposed to the Martian air. The materials in the slots are exposed to the environment and pictures are taken to look at changes in the materials due to, for example, contact with atmospheric dust, exposure to ultraviolet radiation, or Martian magnetic fields. The Magnetic Patches were proposed by a group of Danish scientists to fit into several slots on the patch plate.

Innovation: The patch plate had almost 100 slots to be filled with various materials. The Danish scientists had previously flown magnetic patches on the Mars Pathfinder lander and provided them for the Mars Polar Lander mission. The patches proposed for Project A were of the same exact type used on the Pathfinder mission, modified to fit into the patch plate. Form and function were remained the same and environmental conditions were similar (although the landing sites were different).

Knowledge Generator: The Danish scientists had published numerous papers on the results of their Mars Pathfinder experiments. There was significant publicity about their contributions in the general media (newspapers, tv) and a high level of awareness of their work. They were also regular attendees at various conferences and working group sessions relating to Mars Exploration. The interface requirements for the patch plate experiment were published on the web as part of an educational outreach project conducted with the Planetary Society.

Knowledge Reuser: Scientist at JPL connected the Danish scientists with Engineer at JPL, who then worked with them to incorporate their magnets into the patch plate experiment. Because this was an international partnership and subject to special government regulations, a second Engineer (participant) at JPL worked with the involved parties to enable the exchange of data and facilitate the participation of graduate students from Denmark.

Informants: Scientist = Patch Plate Co-Investigator
 Engineer = Patch Plate Cognizant Engineer
 Engineer (participant) = MECA Instruments Cognizant Engineer

Other re-use cases identified, but not investigated:

- (8) ISE array for MECA Wet Chemistry Cells (Individual Ion Selective Electrodes used for commercial/industrial application, arrayed into a single beaker)
- (9) Paraffin actuator from other space applications to support delivery of soil sample to MECA Wet Chemistry Cells
- (10) Pressure gauge (designed by JPL Engineer) adapted as an ionization sensor in the MECA electrometer.
- (11) Laser Doppler Anemometer for MITCH Weather (DARPA technology development effort extended to provide 3-D wind sensing)
- (12) IMP Camera for MITCH dust devil detection (Reuse of camera and adaptation of camera mast from Mars Pathfinder)
- (13) MITCH pressure/temperature sensors (Adaptation of sensors flown on Viking and Mars Pathfinder)
- (14) MITCH TriboCan and Paschen-Ionization detector (Evolution of the MECA Electrometer)

APPENDIX B

Knowledge Reuse: Interview Questions – Jet Propulsion Laboratory

The purpose of our interview today is to explore the retrospective history of the _____ project. Our goal is to publish and present the information gleaned from our discussions with you and other project participants to the Jet Propulsion Laboratory as a research study, at academic and other conferences or meetings and in an academic journal. I would appreciate your candid and uncensored views and responses. This information will assist us in finding ways to enable knowledge transfer and reuse on future projects at the Jet Propulsion Laboratory.

Your name will not be used in the papers or presentations. However, we would like to use quotes from these interviews and will attribute them to a generic role such as engineer or project manager. I realize that these designations in a small project may still lead those within JPL to be able to attribute the quotes to you. Therefore, if you wish to share information or an opinion that you would prefer to be confidential please let me know.

I would like to start by introducing some definitions that I will be using:

- Knowledge: Explicit information about things and processes that is easily conveyed verbally, through pictures, drawings, diagrams, formulas or writing. Tacit thoughts, ideas, methods and processes that may be difficult to convey to others.
- Knowledge Reuse (KR): Adapting and synthesizing existing components, technologies, techniques, or procedures for use by a different person at a different time and location.
- Common ground: is defined as the beliefs, knowledge and suppositions that the parties believe they share about the joint activity. In this theory, common ground is developed through interactions and communication. The greater the trust between the parties, the greater the opportunity to develop common ground. Dimensions included in this overlap are: mutual understanding of the project objective, technical constraints, organizational constraints, analytic process for problem solving, mutually understood goals, similarity of dedication to resolution. Further, the organization must develop a platform for the encouragement of knowledge development.

(NOTE: The following is a general question to break the ice and ferret out area of particular interest in regard to this research study)

Please describe your part in the Mars project as it pertains to the particular technology or scientific experiment that you were involved in designing. *(NOTE: If it had been suggested by another party that the interviewee be queried regarding a specific experiment or technology, the interviewer would refer to this technology, e.g. “Please tell me about the technology and your work on the Lidar for the MITCH project”).*

- 1) What types of knowledge were reused for this project (e.g., a report, a design, a conversation, data)?
 - a) Let's take them one at a time...I will ask you a number of questions about each of the types of knowledge...Let's start with the _____.
 - b) If there is more than one type of knowledge, please draw a timeline that describes when each knowledge was identified and reused so you can understand the relationship between the types of knowledge sources (e.g., Was there a precedence ordering or accumulation effect?)
- 2) Tell me a bit about the knowledge that you found in this _____.
 - a) How explicit is the knowledge represented in this _____ (e.g., was it all written down or was transferred knowledge primarily tacit)?
 - b) What was the problem that the knowledge was intended to solve?
 - c) How would you have solved the problem without this knowledge?
 - d) What were you doing to solve the problem before you got this knowledge?
- 3) How did you become aware of the knowledge source: (e.g., seminar, discussion, database, knowledge repository, internal web site, conversation)
 - a) If you spoke with someone who helped you find it, who was that person. Was this person a member of a your project group's community of practice, member outside of the of this group, center of excellence publication, job rotation, expert connections directory. Please describe the process by which you located the information.
- 4) The following questions concern the _____'s characteristics that contribute to the process of reuse of the knowledge (common ground):
 - a) How, if at all, did the knowledge itself or the way in which the knowledge was presented, or the context in which the knowledge was presented convey that reuse of that knowledge was a good thing?
 - b) How, if at all, did the knowledge itself, or how the knowledge was presented, or the context in which the knowledge was presented convey that it was high quality, credible, and believable?
 - c) How, if at all, did the knowledge itself, or how the knowledge was presented, or the context in which the knowledge was presented convey the appropriateness of the knowledge to solving or assisting in solving your problem

- d) Did the knowledge that was reused:
 - 1) show more than one perspective on how to solve the problem what were the challenges in the solution space
 - 2) show what was important to your consideration of the problem and solution
 - 3) identify new constraint
- 5) identify what design options were not selected and why
- 6) Rate the order of importance of the following in influencing the fact that you reused the knowledge:
 - a) Content of the knowledge itself helped you to identify new solutions or perspectives
 - b) Immediate and obvious applicability of the knowledge to your problem
 - c) Credibility, quality, and reliability of knowledge
 - d) Incentives or pressures to reuse knowledge
- 7) Were there characteristics of the knowledge or the structure of the group or organization that could have conveyed inverse messages, such as:
 - a) reuse is not a good thing
 - b) information quality is questionable
 - c) information available has limited applicability to different problems
 - d) other reasons
- 8) Did you accept the knowledge as-is or
 - a) (or) did you discuss, contact, debate with the presenter (if it was presented by an individual),
 - b) (or) change the knowledge (if it was a report or database)
 - c) Did you need to do these things in order to:
 - i) develop beliefs about the benefits of reusing knowledge,
 - ii) assure yourself of the quality and appropriateness of the information

- iii) assist in developing multiple perspectives on how to solve the problem? *For example, if the information was presented in a seminar, did the reuser talk to the presenter after the seminar?*
- 9) Why did the you feel it was appropriate to reuse the knowledge?
- 10) *NOTE: This question was not asked, the answer was deduced from other answers:*
Were all four facets of common ground equally important in their contribution to the success of the reuse?
- 11) How important was this reuse to the project?
- 12) Was there a particular event that triggered the reuse?
- 13) Was the knowledge that was reused modified or was it reused as-is?
- 14) Indicate the extent to which each of the following "people-related issues" were likely contributors or inhibitors to the reuse that occurred in this case?
 - a) Experts directory either on line or printed, rolodex etc.
 - i) Team members
 - ii) External sources of knowledge
 - b) Being open to serendipitous collisions – walking the hall and asking people what they are doing or walk in on a seminar, continuous learning
 - c) Culture and norms – reuse is a good thing and therefore I'll share my stuff.
Motivation for reuse.
 - d) How would you phrase the question that would lead to needed knowledge for optimal re-use? Would you generalize the search as "I need a detection device that can be used non-optically"? Would you ask a more specific question?
 - e) What was the role of the leader(s) during the reuse experience?
 - i) Did the leader find or assist in finding the specific artifact?
- 15) What other people were involved in the reuse of the knowledge; who was the knowledge generator?
 - a) Can you draw a network of the people involved and explain their roles?
- 16) What do you think generally contributes to knowledge reuse at JPL.
 - a) What contributed in this case?

APPENDIX C
Knowledge Reuse: email Questionnaire at Jet Propulsion Laboratory

Dear ,

The researchers on the Knowledge Reuse Study, Olivia Neece, Ann Majchrzak and Lynne Cooper, would like to thank you for your cooperation in the study. Thank you for the time you have invested in our project. We need a few more minutes of your time.

A paper is being developed and will be provided to you soon. You will not be mentioned by name in this paper. Rather, we will refer to Engineer or Project Manager in regard to each "case".

After analysis of the data, we decided that four additional questions need to be answered. We would appreciate a quick turn around with answers to these questions within the next week, as we are hoping to send the paper to JPL's document review one week from Tuesday, on December 26. Please press your "reply" button (not reply all) and fill in the answers to each question. This should take only a few minutes and your cooperation will be greatly appreciated.

- 17) How long have you been working in the specific knowledge area of this technology or scientific discipline?
- 18) Were you excited by the prospect of developing this technology or scientific instrument?
- 19) Did you look at this as an opportunity to learn something or would you have preferred to have someone else handle this aspect of the project?
- 20) Did the issue of trust affect your knowledge reuse in this case...for example:
 - a) Did you need to develop some cooperation or interdependence with another person in order to reuse the knowledge?
 - b) Did you need to develop trust in order to reduce your perception of risk in the use of the knowledge?
 - c) Did you need to develop trust in order to believe that the other party would not take advantage of your relationship to the detriment of the project or your position in order to reuse the knowledge?
 - d) Was trust of another party actually a bi-product of the reuse (e.g. through interaction with another individual or group, did a trust relationship develop)?